A systematic approach to designing Multi-Experiment Platforms forlong duration ballooning

A SYSTEMATIC APPROACH TO DESIGNING MULTI-EXPERIMENT PLATFORMS FOR LONG DURATION BALLOONING

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ABSTRACT

The interest in LDB flights has grown dramatically over the years. However, since the success of a mission is strongly dependent on the costs, one possible way to improve the overall efficiency of a campaign is to perform different experiments during the same flight, even though this requires more versatile platforms. The design of this kind of system is very difficult to accomplish.

In this paper the authors discuss the main issues related to the design of multi-experiment platforms for LDB flights, and try to provide some guidelines for making the approach more systematic. An application to a two-experiment platform design problem is also briefly described.

1. INTRODUCTION

Interest in Long-Duration Ballooning and, recently, in Ultra-Long-Duration Ballooning has grown over the years as a means of performing experiments over a long duration time at high altitude. However, the success of a mission is dependent on the scientific results obtained by the experiment, and also depends on the overall costs of the whole campaign. Many times, the cost of a campaign, is the factor that, , by itself, determines whether a mission should be performed or not, without taking into account any other kind of criteria such as the scientific interest of the experiment, the scientific relevance of the results that may be obtained, etc. Minimization of the cost of the whole campaign represents a very critical issue to be considered.

As stated in [1], one possible way to improve the overall efficiency of a mission is to perform different kinds of experiments during the same flight and, naturally, to reuse resources from previous missions in order to reduce the overall costs. Improving the platform concept according to the multi-experiment criterion requires maximizing the ratio between the payload and the lift capacity of the balloon by reducing the mass of each system in order to increase the number of experiments that may be performed during the same flight. It also means satisfying a lot of possibly contradictory specifications among the functional requirements of the different experiments. The reusability of systems such as power supply systems, the pivot system, etc., requires the definition of lightweight technical solutions capable of preserving their integrity during various flights.

Within this framework, a small Italian Consortium, set up by IFAC-CNR of Florence, the Universities of Florence and Bologna, LEN of Genova, and the IASF of Bologna, has been established for the purpose of pursuing these objectives on the base of the first step towards the optimization of platforms according to the multi-experiment concept presented in [2]. There, the design of a platform having a certain degree of versatility was described, and the use of problem-solving techniques was proposed, together with the integration of different simulation and virtual prototyping tools, as a means of speeding up the design of new, original technical solutions able to meet multi-experiment requirements.

According to the requirements described so far, the design of multi-experiment platforms cannot be addressed by using heuristic and specific approaches. On the contrary, it requires the definition of more systematic methodologies. Within this context, the aim of this paper is to introduce and discuss the main issues related to the systematic design of multi-experiment LDB platforms by taking into account the above-mentioned requirements as design criteria. More in detail, in Section 2 the general approach under investigation for supporting the design of multi-experiment platforms is presented, and a synthesis of its application to a two-experiment platform is described in Section 3. Lastly, conclusions and discussions are provided in Section 4.

2. DESIGN CRITERIA FOR MULTI-EXPERIMENT PLATFORMS

An LDB platform may be considered as a technical system that is designed to perform certain kinds of functions under well-established performance criteria. Over the years, many rational methods have been suggested for addressing the systematic design of technical systems such as those in [3, 4]. These methods are able to cover all the aspects related to the design process, ranging from a identification of the design objectives to the detailed design. An integration of these techniques is under investigation in order to supply some guidelines to support the design of LDB platforms. The framework of this methodology is shown in Fig. 1.

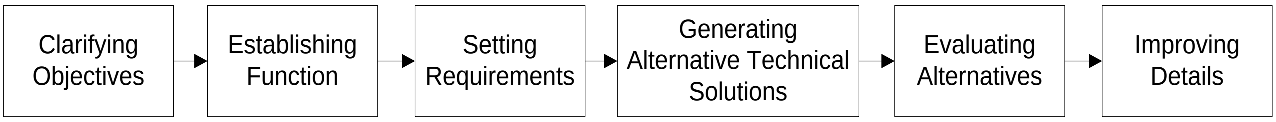

Figure 1: The proposed road-map to support the design of multi-experiment platforms.

According to the figure, this model consists of six main steps: here as follows, this approach will be described in detail and the main issues related to the application of the model to the design of multi-experiment platforms will be introduced.

2.1 *Clarifying Objectives*

The starting point for a given design of a technical system requires a definition of the objectives that the system needs to meet. Typically, the problem of the design is an ill-defined problem when the starting point and the end point are not well established.. The aim of the first step of the procedure is, therefore, to identify these points in terms of design purpose.

The Tree of Objectives method is a suitable tool for supporting the identification of the design objectives. It requires performing the following steps:

1. **Preparation of a list of design objectives**: these are obtained in the form of design purposes through questions to the client and discussion within the design team.
2. **Organization of the list into sets of higher-level and lower-level objectives**: the list of design objectives obtained in the previous step is expanded from a general level to a more detailed level, and it is organized into hierarchies in order, from the main objectives to the sub-objectives.
3. **The drawing of a diagrammatic tree of objectives that shows the hierarchical relationships and interconnections**: the hierarchical order identified in the previous step is translated into a diagrammatic tree of design objectives that shows the relationships existing among them.

At the end of these steps a clear and understandable representation of "client" requirements is obtained. These requirements represent a first model of the system to be designed.

2.2 Establishing Function

Once the purposes of the design have been identified, the next step requires defining both the functional requirements of the system and the problem level. In other words, this phase enables the designer to answer the question: "what should the system perform?"

The Function Analysis Method offers a means for considering the overall functions and the level at which the problem must to be addressed. The overall functions of a system are represented by the ones that it will have to satisfy in order to meet the functional requirements. Instead, the problem level is defined by establishing the boundary of the functional model around a sub-set of functions. The procedure for performing the Function Analysis is the following:

1. **The black box representation of the overall function**: expresses the overall function of the system as a black box in which the flow of energy, materials and signals in inputs are converted into outputs.
2. **A breakdown of the overall functions into sets of essential sub-functions**: the sub-functions take into account the tasks that have to be performed inside the black box.
3. **The drawing of a block diagram**: the black boxes are organized into a diagram and the sub-functions are linked together according to the flow of energy, materials and signals that they exchange.
4. **The drawing of the system boundary**: the system boundary is identified by the functional limits of the device to be designed.

At the end of this phase, the functional model of the system is obtained. This model represents a general description of the technical solution that needs to be selected.

2.3 Setting Requirements

Performance requirements are sometimes regarded as being design objectives and functions, but this is not totally correct. As described so far, the functions and design objectives are related only to what a device should perform. Furthermore, they do not suggest precise qualitative and quantitative limits. The performance specifications define the limits within which an identified solution performing a function may be considered as acceptable. Thus, the aim of this phase is to identify a set of limits for the overall dimensions, the power consumption, the mass, costs, efficiency, etc., that the system has to satisfy. These limits become criteria for selecting the most suitable design solutions. To identify the performance requirements, the following guidelines need to be addressed:

1. **A consideration of the level of generality of the solution to which the performance requirements refer**: a specification at too high a level of generality cannot suggest a

selection criteria, while too low a level may limits the freedom of the designer to create acceptable solutions. A classification of the level from the most general to the most detailed could be the following:

- product alternatives;
- product types;
- product features.

2. **Identification of the required performance attributes**: any product, device or machine has a set of attributes, and it is these that are specified in the performance specifications. The attributes should be stated in a way that is independent of any particular solution.
3. **A statement of the precise performance requirements for each attribute**: the specifications should be expressed, where possible, by quantified terms ranging between limits.

2.4 Generating alternative Technical Solutions

The problem addressed in this phase is the way to find more technical solutions for performing each function of the system that has been identified by the functional model. Over the years, many problem-solving techniques have been suggested for supporting the designer. As suggested by [4], the main step of this phase requires:

1. **A definition of the working principle**: in this step, a physical principle for performing a function is identified. This requires the identification of all kinds of resources available within the system which could be used to perform the function.
2. **A definition of the working structure**: once the working principle has been defined, it is translated into one or more schemes which represent a first concept of the technical solution used to perform the function.

At the end of this phase, a set of concepts for each function of the system is identified.

2.5 Evaluating Alternatives

The solutions generated in the previous step for each function are evaluated according to the objectives of the design and to the performance specifications. This makes it possible to choose the final design of the system. The evaluation of the alternatives is made in accordance with to the following principle:

1. **Identification of the relative importance of the design objectives**: this is done by using the same criteria used to assign the priorities in customer requirements. Usually, numbers in the range between 0 and 1 are used.
2. **Establishing of the performance parameters for each objective**: this requires defining the performance specifications for each design objective. The acceptable limits of a solution should be reduced to a mono-scale utility score.
3. **Calculatation of the score of each technical solution**: the product of the weighted objective for the score utility is calculated for each solution. The solution having the highest score sum represents the best design.

Such criteria try to systematize the decision of the designer. However, a comparison and discussion of the utility score profiles among the different solutions may be a better decision criterion than simply choosing the "best".

2.6 Improving Details

Once the technical solutions have been selected, the embodiment design starts. In this phase, the concept design is further developed down to the detailed final solution. A knowledge of the relationships between customer requirements and the design parameters enables the designer to complete optimization of the system, and the massive use of CAD/CAE tools can speed up the design process.

3. A POSSIBLE APPLICATION

An application of the road-map to design a two-experiment platform is briefly described here as follows. The experiments involved are the following:

- **Experiment 1**: earth observation, mass: 150 kg, power consumption: 0.1 kWh, duration: 10 days, time of observation: during the presence of the sun light;
- **Experiment 2**: star observation in the anti-sun direction, power consumption 0.3 kWh, mass: 250 kg, duration: 12 days, time of observation: h 24;

Since these requirements may be considered as customer requirements, they are boundary conditions of the design problem.

The first step of the road-map suggests identifying the main objectives of the design and organizing them into a hierarchical tree. As shown in Fig. 2, the main objective is represented by the needs to minimize the overall cost of the whole campaign. As introduced, this concept means performing more experiments during the flight and reusing the maximum number of flight systems for other campaigns.

Going to a more detailed level, the multi-experiment objective requires having systems with low mass and inertia properties and a high payload, lift capability ratio. Moreover, a high level of versatility in the

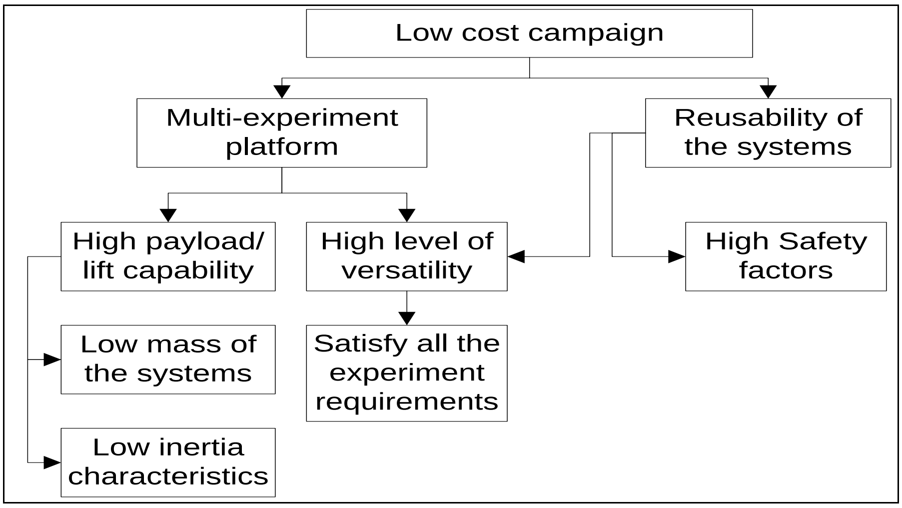

Figure 2: Design objectives related to the platform, organized in a hierarchical tree

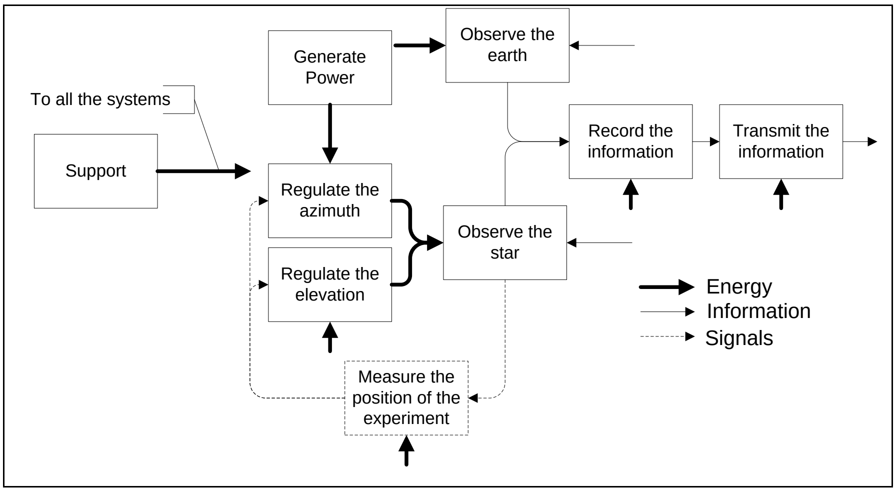

Figure 3: Functional model of the platform. The arrows represent the flow of energy, information and signals exchanged among the functions.

platform is needed in order to satisfy all the experiment's requirements. Reusability is another key issue: in order to reuse systems, they have to survive different campaigns. Therefore, both high safety factors and levels of versatility are required.

Once the design objectives have been identified, the next step requires a defining of the functional model of the system. In Fig. 3 such a model is shown. It is reduced to a mean level of detail in terms of sub-functions. The energy, information and signal flows among the functions of the system are also shown. The experiments are represented in terms of the functions that they should perform. Both experiments have to observe something, record the information, and transmit it. A regulation of the azimuth and the elevation is required for experiment 2 with respect to the portion of sky to be observed, so a system providing these functions should be designed. This model represents a first solution to the design problem at a high level of abstraction.

Once the functional model has been defined, the next step is the definition of the requirements that provide the criteria for selecting the technical solutions. A synthesis of these specifications is presented in Table 1; however, the entire list is omitted because of its length.

Table 1: System requirements

Requirements	**Value**
Power supply	= 1 kWh (+ 0.5 kWh in 1 min for overload)
Regulation speed	= 16 °/min. (+/- 1°/min.)
Range of temperature	-40°C < T < +85 °C
Overall dimensions	3 m X 3 m X 3 m
Mass of the power system	As minimal as possible
Mass of the regulation system	As minimal as possible
Overall Mass	< 3000 kg

A set of technical solutions should now be identified for each function of the system. Here, only the power system supply will be taken into account. According to the road-map, in order to generate alternative solutions, first a working principle has to be identified on the base of the resources available in the system. Then the working principle will be translated into a working structure. The following solutions have been generated:

- Solar panels;
- Fuel cells;

The solar panels use the energy of the sun to produce electrical power. Moreover, the sun is the only available resource that may be exploited. The fuel cells generate electrical power by exploiting a chemical reaction.

The evaluation of these technical solutions is performed according to the design objectives shown in Fig. 2, the requirements summarized in Table 1, and the requirements of the experiments. For each design objective, a weight establishing the relative importance has been defined by assigning a value between 0 and 1. The utility score set for both solutions ranges from 1 to 5. A low value means that the solution does not meet the requirements very well. In Tables 2 and 3, the scores and the total for both the solutions are summarized.

Table 2: Evaluation of the solar panel solution

Objective	**Weight**	**Score“1”**	**S X W**
Reusability	0.17	2	0.34
Versatility	0.17	5	0.85
Cost	0.17	4	0.68
Mass	0.13	4	0.52
Power	0.13	4	0.52
Operational time	0.13	2	0.26
Overload	0.05	3	0.15
Temperature	0.05	5	0.25
		TOTAL	**3.57**

Table 3: Evaluation of the fuel cell solution

Objective	**Weight**	**Score“1”**	**S X W**
Reusability	0.17	4	0.68
Versatility	0.17	5	0.85
Cost	0.17	2	0.34
Mass	0.13	2	0.26
Power	0.13	4	0.52
Operational time	0.13	5	0.65
Overload	0.05	3	0.15
Temperature	0.05	2	0.10
		TOTAL	**3.55**

As can be seen, the two technical solutions have almost the same final score. Even thought the fuel cells are able to supply energy in 24 h, making sky observations possible also during the night, a more thorough analysis of both solutions suggests that the solar panels are more suitable for flights of long duration since they have less mass than the fuel cells system since this one requires too much fuel (this also means additional costs).

For flights of short duration that require observations in 24 h, the fuel cell system is more suitable than the solar panels in terms of cost, mass and power. Another important issue for the reusability objective is protection against damage during the landing phase. The solar panels require structural solutions devoted to protecting the system, while the fuel cells can be embedded within the gondola frame without any kind of protective system. Therefore, in the reusability score, also a fact of this type is taken into account.

Both solutions have been further developed, and a detailed design has been completed. The results have been summarized in [5].

4. CONCLUSIONS

In the paper, several guidelines to assist in the design of multi-experiment platforms have been presented. These guidelines have been integrated in a road-map that has been described in detail. An application of the road-map for designing a two-experiment platform has been briefly presented.

A road-map of this type will be further developed by the designer in order to make its application easier. In future, it will be interesting to extend this kind of systematic approach to the design of the entire experiment campaign.

5. REFERENCES

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